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WATERTOWN ARSENAL
LABORATORY

MEMORANDUM REPORT

NO. WAL 710/716

Metallurgical Examination of Twelve 2 $\frac{1}{2}$ " Thick Rolled Homogeneous
and Sixteen 2 $\frac{1}{2}$ " Thick Face Hardened Armor Plates Manufactured
by Carnegie-Illinois Steel Corporation

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Final Report on Problem B-4.54

19 January 1945

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and Sixteen $2\frac{1}{2}$ " Thick Face Hardened Armor Plates Manufactured

by Carnegie-Illinois Steel Corporation



ABSTRACT

A metallurgical examination was conducted on twelve (12) $2\frac{1}{2}$ " thick rolled homogeneous and sixteen (16) $2\frac{1}{2}$ " thick rolled face hardened armor plates manufactured by Carnegie-Illinois Steel Corporation on OCO-D Project 1558. The results of this investigation indicate that, in general, the steel soundness of the face hardened plates was inferior to that of the homogeneous plates. In this connection, the face hardened plates had more pronounced directional properties than the homogeneous plates. The average Brinell hardness of the homogeneous plates was 247-262. The average Brinell hardness of the face hardened series was found to be face, 465-690, and core 208-243. The depth of the effective case at Rockwell C 50 varied from .26"-.40" in from the face of plate (10 plates tested) while in two face hardened plates the case depth was .09"-.16" in from face of plate. In general, the homogeneous and face hardened plates were properly heat treated resulting in fibrous fractures, good V-notch impact properties and a satisfactory microstructure.

1. As requested by the Ordnance Research Center, Aberdeen¹, metallurgical examination has been completed on twelve samples of $2\frac{1}{2}$ " thick rolled homogeneous armor and sixteen samples of $2\frac{1}{2}$ " thick rolled face hardened armor plates manufactured by the Carnegie-Illinois Steel Corporation on OCO-D Project 1558. Due to the fact that the first set of

1. APG 470.5/529 - Wtn 470.5/8399(r) - 24 August 1944

sixteen face hardened sections were cut from the edge of the plates, it was impossible to determine an accurate measurement of depth of case. It was observed that near the edge of the plate the case decreased in thickness to a marked degree. It was, therefore, requested that another set of sixteen face hardened sections be forwarded to this arsenal for accurate case depth measurements and that each section be cut from near the center of the ballistic test plate. In reply to this request only twelve samples were submitted. Sections from plate Nos. 41-3/8, 41-3/4, 41-13/16 and 441 were not available for examination. It was reported that the ballistic properties of the face hardened plates were inferior to those of the homogeneous plates.

2. The purpose of this investigation was to conduct an examination of the samples to determine if there was a metallurgical variation among the homogeneous or the face hardened plates that might affect the ballistic results.

3. The plates under investigation are listed as follows:

<u>2 1/2" Thick Rolled Homogeneous Plates</u>	<u>2 1/2" Thick Face Hardened Plates</u>
11A	41 1/16
21A	41 1/8
21B	41 3/16
21C	41 1/4
21D	41 5/16
31A	41 3/8
31B	41 7/16
41A	41 1/2
41B	41 9/16
41C	41 5/8
41D	41 11/16
51B	41 3/4
	41 13/16
	41 7/8
	41 15/16
	441

4. The results obtained from tests conducted on the twelve homogeneous plates indicated that five plates had a steel soundness rating of "D" while the remainder had "B" and "C" ratings. With the exception of one sample which showed a trace of crystallinity all samples were properly heat treated. Generally speaking, the face hardened plates had more pronounced directional properties than the homogeneous plates as shown by V-notch impact tests and tensile tests. It was noted that the face hardened plates exhibited various degrees of "woodiness" in the fractures made on sections near the edges of the plates. In one case a "D" rating was observed in a center section of a face hardened plate while the remaining center sections had "B" and "C" ratings. The carburized cases exhibited a fine silky fracture. The homogeneous plates

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and the face hardened plates were properly heat treated as shown by the satisfactory V-notch impact properties at -40°F. The homogeneous plates were heat treated to a Brinell hardness range of 247-262. The Brinell hardness of the face hardened plates was as follows, face hardness, 465-690, and core hardness, 208-243. In general the face hardness near the center of the carburized plates was slightly lower than the face hardness near the edge of the plate while the core hardness near the center of these plates was slightly higher than the core hardness near the edge of the plates. In a series of ten face hardened plates the effective case depth to Rockwell C 50 varied from .26" to .20" in from the face of the plate. In two face hardened plates, however, the case depth to Rockwell C 50 was only .09" to .16". Furthermore, the case depth to Rockwell C 40 varied from .58" to .80" in from the face of the plates. The microstructure of the homogeneous plates consisted of tempered martensite. The carburized cases of the face hardened plates were fairly free from pronounced carbide segregations while the cores had a structure similar to that of tempered bainite.

5. The metallurgical examination consisted of the following tests:

- a. Chemical analyses of selected plates.
- b. Fibre fracture test.
- c. Fracture test for steel quality.
- d. Brinell hardness surveys.
- e. Rockwell C hardness surveys.
- f. V-notch Charpy impact tests.
- g. Tensile tests.
- h. Microscopic examination.

6. The results of the metallurgical examinations are as follows:

- a. Chemical Analyses. Chemical analyses of representative samples are given in Table I.
- b. Fibre Fracture Test. Fibre fracture tests were made on properly notched sections and the steels rated with respect to their heat treated condition, the results of which are given in Tables IV and V. All of the face hardened plates fractured in a fibrous manner and all except one of the rolled homogeneous plates were fibrous. The carburized cases were silky.

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c. Fracture Test for Steel Quality. The results of this test indicated that of the rolled homogeneous plates, five had a steel soundness rating of "D" while the remainder were satisfactory. The samples removed from the edge of the face hardened plates exhibited various degrees of woodiness. The central areas of these face hardened plates did not exhibit this woodiness to such a pronounced degree as noted in the edges. One sample, No. 41-5/16 exhibited a "D" fracture in the central area of the plate. The results of the fracture tests are given in Tables IV and V.

d. Brinell Hardness Surveys. Brinell hardness readings were taken on the surface and cross section of the homogeneous plates. On the face hardened series, Brinell readings were taken on the face and cross sections of the core. All readings were equidistantly spaced throughout the sections tested. The hardness values are listed in Tables II and III. It was noted, in most of the face hardened plates, that in the core hardnesses taken on samples from the edge of the plates the immediate center of the core had a Brinell hardness which was 20-30 points higher than the rest of the section. This may be due to metallic segregation present in the center of the cross section.

e. Rockwell C Hardness Surveys. Rockwell C surveys were made at .05" intervals across the carburized zone, see Figures 1 and 2. The case depth to Rockwell C 40 varied from .58" to .80" in from the face of the plate. The case depth to Rockwell C 50 which may be termed the effective case varied from .26" to .40" in from the face of the plate. In two face hardened plates, however, the case depth to Rockwell C 50 was only .09" to .16".

f. V-Notch Charpy Impact Tests. The results of the V-notch Charpy impact tests made on representative samples taken in longitudinal and transverse directions of the homogeneous and face hardened plates are given in Tables IV and V. The values obtained indicate that the plates were properly heat treated and correlate with the results received in the fibre fracture test. Generally speaking, the face hardened plates had more pronounced directional properties than the homogeneous plates as shown by V-notch impact tests.

g. Tensile Tests. Tensile tests made in the longitudinal and transverse directions on samples are given in Table VI. The results of these tests indicate that the face hardened plates exhibited greater directional properties than the homogeneous plates.

h. Microscopic Examination. The pronounced "woody" condition noted near the edge of some of the face hardened plates was associated with a segregation of alumina streaks. Face hardened plates which only exhibited a trace of woodiness near the edge contained a series of short fine manganese sulphide inclusions. The central areas of the face hardened plates contained occasional sulphide-silicate nonmetallic inclusions. No marked segregation of nonmetallic inclusions was detected in the series of homogeneous plates. Apparently the directional properties noted in the face hardened plates were associated with the elongated nonmetallic inclusions detected in these samples.

The microstructure of the rolled homogeneous plates is typical of tempered martensite. The microstructure of the outer cases of the carburized plates consisted of some excess fine carbides in a martensitic matrix whereas in the inner cases the carbides were of the globular type. This correlates with the silkiness of the carburized cases obtained when fractured. The microstructure of the cores consisted of a uniform distribution of fine carbides in a matrix similar to tempered bainite. Photomicrographs are presented which illustrate typical microstructures of the outer and inner carburized cases and cores of the face hardened plates, see Figures 3 and 4.

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TABLE I

Chemical Analyses

Plate No.	Type of Armor	Thick- ness	C	Mn	Si	S	P	Ni	Cr	Mo	V	Cu	B	Ti	Zr
11 A	Rolled Homogeneous	2 $\frac{1}{2}$ "	.29	1.29	.29	.015	.017	.69	.81	.33	Nil	.13	Tr	Tr	Nil
21 A	"	2 $\frac{1}{2}$ "	.28	1.32	.27	.015	.017	.69	.80	.33	Nil	.13	.0009	Tr	Nil
31 A	"	2 $\frac{1}{2}$ "	.285	1.33	.29	.016	.018	.71	.84	.33	Nil	.125	Tr	Tr	Nil
41 C	"	2 $\frac{1}{2}$ "	.30	1.36	.27	.021	.018	.69	.84	.32	Nil	.12	Tr	Tr	Nil
41-1/16	Face Hardened	2 $\frac{1}{2}$ "	.305	.23	.05	.020	.013	3.70	1.75	Nil	Nil	.055	Tr	Nil	Nil
41-7/16	"	2 $\frac{1}{2}$ "	.355	.21	.05	.023	.009	3.80	1.76	Nil	Nil	.04	Tr	Nil	Nil
41-9/16	"	2 $\frac{1}{2}$ "	.25	.22	.06	.020	.008	3.76	1.83	Nil	Nil	.055	Tr	Nil	Nil
441	"	2 $\frac{1}{2}$ "	.26	.21	.06	.020	.007	3.78	1.78	Nil	Nil	.06	Tr	Nil	Nil

TABLE II

Results of Brinell Hardness Survey Conducted on $2\frac{1}{2}$ " Thick

Rolled Homogeneous Armor Plates

<u>Plate No.</u>	<u>Surface Hardness</u>		<u>Cross Section Hardness</u>	
	<u>Range</u>	<u>Average</u>	<u>Range</u>	<u>Average</u>
11A	255	255	248-255	253
21A	255-262	261	255-269	262
21B	262-269	263	255-262	258
21C	255-262	260	255-262	258
21D	262-269	267	262-269	263
31A	255-262	258	248-255	253
31B	255-262	257	248-262	255
41A	248-255	251	241-255	247
41B	248-255	251	248-255	251
41C	248-262	257	241-255	250
41D	248-255	253	241-255	249
51B	255-269	264	255-269	259

TABLE III

Results of Brinell Hardness Survey Conducted on 2 $\frac{1}{2}$ " Thick RolledFace Hardened Armor Plates

Plate No.	Face				Cross Section of Core			
	Center		Edge		Center		Edge	
	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.
41 1/16	601-627	607	653	653	223-229	226	207-229	212
41 1/8	601	601	555-601	570	217-223	220	217	217
41 3/16	601	601	555-578	563	223-229	225	217-223	218
41 1/4	627	627	534-555	549	241-248	243	223-229	226
41 5/16	495-555	518	627-653	644	229-235	231	217-229	223
41 3/8	---	---	534-601	563	---	---	217	217
41 7/16	601	601	555-601	584	223-255	233	207-212	211
41 1/2	653	653	653	653	223-235	231	217-223	221
41 9/16	555-578	560	627-682	654	212-229	219	223-229	225
41 5/8	578	578	601-653	627	212-229	216	212-217	215
41 11/16	444-477	465	627	627	241	241	212-217	215
41 3/4	---	---	601-627	618	---	---	212-223	228
41 13/16	---	---	682-712	690	---	---	212-223	216
41 7/8	514-534	522	653-712	682	229-235	233	207-212	208
41 15/16	601-627	617	627-653	644	212-255	230	207-223	211
441	---	---	514-601	572	---	---	207-217	212

TABLE IV

Summary of the Results of Tests Conducted on 2 1/2" Thick Rolled Homogeneous A

Plate No.	Fracture Tests		Ave. Cross Sectional Area	Direction of Rolling	*V-Notch Charpy
	Fibre	Steel Quality			Pt./Lbs.
11A	**F	B	253	Longitudinal Transverse	72.8 57.7
21A	F	B	262	Longitudinal Transverse	71.3 54.1
21B	F	C	258	---	---
21C	F	C	258	---	---
21D	F	D	263	---	---
31A	F	D	253	Longitudinal Transverse	74.7 61.4
31B	F	C	255	---	---
41A	F	D	247	---	---
41B	F	B	251	---	---
41C	F	D	250	Longitudinal Transverse	80.6 62.3
41D	F	D	249	---	---
51B	F-Tr. of crystallinity C		259	---	---

**F-- Fibrous

* All V-notch Charpy bars were cut from the midwall of the plates.

Midwall indicates a position halfway between the center and surface of the plate.

TABLE IV

Conducted on 2 1/2" Thick Rolled Homogeneous Armor Plates

		*V-Notch Charpy Impact Tests			
Test No.	Direction of Rolling	+70°F		-20°F	
		Ft./Lbs.	Fracture	Ft./Lbs.	Fracture
	Longitudinal	72.8	F	71.3	F
	Transverse	57.7	F	55.0	F
	Longitudinal	71.3	F	69.8	F
	Transverse	54.1	F	51.9	F
	Longitudinal	---	---	---	---
	Transverse	---	---	---	---
	Longitudinal	74.7	F - Tr. woodiness	71.3	F
	Transverse	61.4	F	56.4	F
	Longitudinal	---	---	---	---
	Transverse	---	---	---	---
	Longitudinal	80.6	F - some woodiness	71.3	F - some woodiness
	Transverse	62.3	F	59.6	F
	Longitudinal	---	---	---	---
	Transverse	---	---	---	---

if the plates.
 Inter and surface of the plate.

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Sample No.	*Case Depth to		Fracture Tests				*Hardness Survey		
	Ro 40	Ro 50	*Fibre		Steel Quality		Maximum Ro Hardness of Case	Average Har	
			Core	Case	Edge	Center		BHN	B
41 1/16	.74"	.40"	Fibrous	Silky	B moderate woody	B	54.5	226	
41 1/8	.70"	.38"	Fibrous	Silky	B moderate woody	B	56.5	220	
41 3/16	.58"	.36"	Fibrous	Silky	B moderate woody	B	55.0	225	
41 1/4	.60"	.36"	Fibrous	Silky	B moderate woody	B	57.5	243	
41 5/16	.58"	.09"	Fibrous	Silky	B pronounced woody	D	50.5	231	
41 3/8	--	--	--	--	B pronounced woody	-	--	-	
41 7/16	.68"	.30"	Fibrous	Silky	B moderate woody	B	55.5	233	
41 1/2	.80"	.26"	Fibrous	Silky	B moderate woody	B	56.5	231	
41 9/16	.58"	.16"	Fibrous	Silky	C pronounced woody	C	53.5	219	
41 5/8	.63"	.36"	Fibrous	Silky	B pronounced woody	B	54.5	216	
41 11/16	.80"		Fibrous	Silky	B pronounced woody	B	50.0	241	
41 3/4	--	--	--	--	B pronounced woody	-	--	-	
41 13/16	--	--	--	--	C pronounced woody	-	--	-	
41 7/8	.65"	.26"	Fibrous	Silky	B pronounced woody	B	51.5	233	
41 15/16	.64"	.40"	Fibrous	Silky	C pronounced woody	C	56.0	230	
441	--	--	--	--	B moderate woody	-	--	-	

NOTE: V-notch Charpy bars were taken from midwall section of plates. Midwall in face harden

*Samples taken from central areas of ballistic test plate.

**Samples taken from areas near edge of ballistic test plate.

Summary of Results of Tests Conducted on 1/2" x 1/2" x 1/2" Plates

by enter	*Hardness Survey			Direction of Rolling	+70°F. Ft/Lbs.	Y-Notch Char Fracture
	Maximum Rc Hardness of Case	Average Hardness of Core BHN	Rc Converted			
B	54.5	226	19			
B	56.5	220	18			
B	55.0	225	19			
B	57.5	243	23			
D	50.5	231	21			
-	--	-	--			
B	55.5	233	21.5	*Longitudinal *Transverse **Longitudinal **Transverse	106.2 67.5 103.6 65.6	Fibrous Fibrous Fibrous Fibrous
B	56.5	231	21			
C	53.5	219	17.5	*Longitudinal *Transverse **Longitudinal **Transverse	131.3 46.6 98.5 67.0	Fibrous (wo Fibrous (broken of lamina Fibrous (broken of lamina Fibrous (wo
B	54.5	216	17.5			
B	50.0	241	23			
-	--	-	--			
-	--	-	--			
B	51.5	233	21.5			
C	56.0	230	20.5	**Longitudinal **Transverse	127.0 74.2	Fibrous (wo Fibrous (broken of lamina
Y-	--	-	--	**Longitudinal **Transverse	112.2	Fibrous (tr of wo Fibrous

Location of plates. Midwall in face hardened plate refers to a position halfway between the center

test plate.
to test plate.

V-Notch Charpy Impact Tests

direction of Rolling	+70°F.	Fracture		-40°F.	Fracture	
	Ft/Lbs.			Ft/Lbs.		
Longitudinal	106.2	Fibrous		101.6	Fibrous	
Transverse	67.5	Fibrous		65.6	Fibrous	
Longitudinal	103.6	Fibrous		113.7	Fibrous	
Transverse	65.6	Fibrous		67.5	Fibrous (woody)	
Longitudinal	131.3	Fibrous (woody)		90.3	Fibrous (woody)	
Transverse	46.6	Fibrous (broken ends of laminations)		47.5	Fibrous (broken ends of laminations)	
Longitudinal	98.5	Fibrous (broken ends of laminations)		98.5	Fibrous (broken ends of laminations)	
Transverse	67.0	Fibrous (woody)		67.5	Fibrous (woody)	
Longitudinal	127.0	Fibrous (woody)		99.5	Fibrous (woody)	
Transverse	74.2	Fibrous (broken ends of laminations)		65.6	Fibrous (broken ends of laminations)	
Longitudinal	112.2	Fibrous (tr of woodiness)		112.2	Fibrous	
Transverse		Fibrous		77.6	Fibrous	

to a position halfway between the center and rear face.

3

Table V

TABLE VI

Tensile Tests

Test Bar .357" Diameter

Plate No.	Type	Location of Test Specimen	Direction	I.S. Lbs./Sq.In.	T.S. Lbs./Sq.In.
11A	Homogeneous	Midwall	Longitudinal	105,500	124,000
11A	Homogeneous	Midwall	Transverse	106,500	125,500
21A	Homogeneous	Midwall	Longitudinal	110,000	128,000
21A	Homogeneous	Midwall	Transverse	109,500	130,500
31A	Homogeneous	Midwall	Longitudinal	107,500	125,500
31A	Homogeneous	Midwall	Transverse	107,500	125,000
41C	Homogeneous	Midwall	Longitudinal	103,750	123,000
41C	Homogeneous	Midwall	Transverse	103,120	122,500
41 7/16	Face Hardened	Midwall	*Longitudinal	100,000	135,000
41 7/16	Face Hardened	Midwall	*Transverse	114,000	157,000
41 7/16	Face Hardened	Midwall	**Longitudinal	80,000	105,000
41 7/16	Face Hardened	Midwall	**Transverse	82,500	106,000
41 9/16	Face Hardened	Midwall	*Longitudinal	93,500	131,500
41 9/16	Face Hardened	Midwall	*Transverse	87,500	125,000
41 9/16	Face Hardened	Midwall	**Longitudinal	80,000	107,900
41 9/16	Face Hardened	Midwall	**Transverse	84,500	108,800
41 15/16	Face Hardened	Midwall	**Longitudinal	77,500	102,000
41 15/16	Face Hardened	Midwall	**Transverse	80,500	100,900
441	Face Hardened	Midwall	**Longitudinal	80,000	104,000
441	Face Hardened	Midwall	**Transverse	83,750	106,000

NOTE: Midwall indicates a position halfway between the center and surface of the plate.
 Midwall in face hardened plate refers to a position halfway between the center and surface of the plate.
 *Samples taken from central areas of ballistic test plate.
 **Samples taken from areas near edge of ballistic test plate.

Test Bar .357" Diameter

ion of specimen	Direction	Y.S. Lbs./Sq.In.	T.S. Lbs./Sq.In.	% El.	% R.A.	Average Cross-Sectional BHN
wall	Longitudinal	105,500	124,000	22.1	64.4	253
wall	Transverse	106,500	125,500	20.0	58.9	
wall	Longitudinal	110,000	128,000	20.7	63.7	262
wall	Transverse	109,500	130,500	20.0	38.9	
wall	Longitudinal	107,500	125,500	20.7	62.0	258
wall	Transverse	107,500	125,000	20.0	59.6	
wall	Longitudinal	103,750	123,000	21.4	63.7	250
wall	Transverse	103,120	122,500	20.7	58.9	
Average Cross Section of Core - BHN						
Near Edge of Plate Near Central Area of Plate						
wall	*Longitudinal	100,000	135,000	17.9	56.3	233
wall	*Transverse	114,000	157,000	12.9	38.9	
wall	**Longitudinal	80,000	105,000	26.4	71.6	211
wall	**Transverse	82,500	106,000	25.0	66.0	
wall	*Longitudinal	93,500	131,500	17.9	55.9	219
wall	*Transverse	87,500	125,000	18.6	53.3	
wall	**Longitudinal	80,000	107,900	25.0	70.7	225
wall	**Transverse	84,500	108,800	23.6	61.3	
wall	**Longitudinal	77,500	102,000	25.0	72.5	211
wall	**Transverse	80,500	100,900	23.6	59.9	
wall	**Longitudinal	80,000	104,000	26.4	71.6	212
wall	**Transverse	83,750	106,000	25.0	63.4	

tion halfway between the center and surface of the plate.

White refers to a position halfway between the center and rear face.

1 areas of ballistic test plate.

near edge of ballistic test plate.

2

2 $\frac{1}{2}$ " FACE HARDENED ARMOR
MADE BY CARNEGIE-ILLINOIS STEEL CORPORATION
ROCKWELL "C" HARDNESS SURVEYS ACROSS THE CARBURIZED CASE

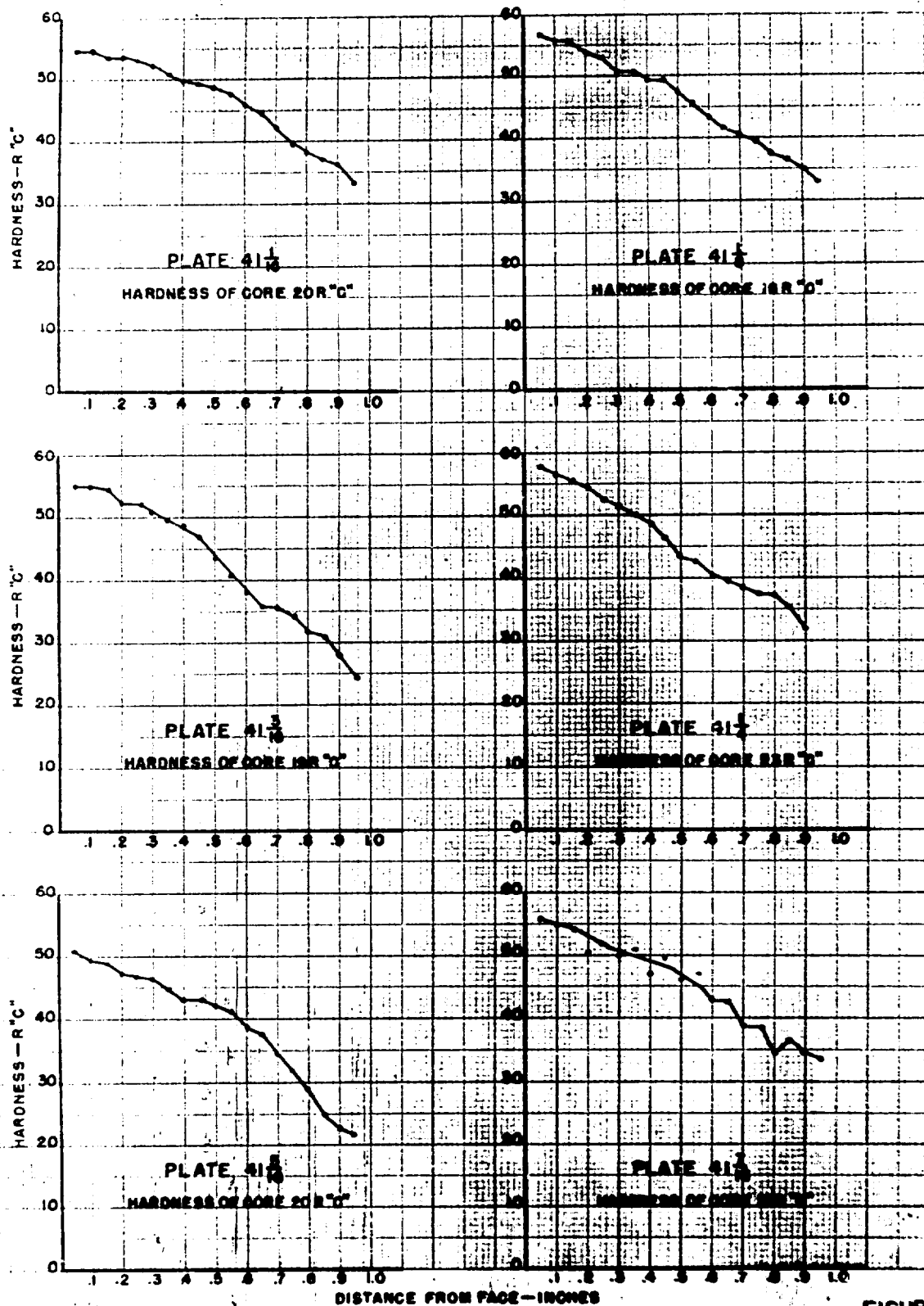


FIGURE 1

2 $\frac{1}{2}$ " FACE HARDENED ARMOR
MADE BY CARNEGIE-ILLINOIS STEEL CORPORATION
ROCKWELL "C" HARDNESS SURVEYS ACROSS THE CARBURIZED CASE

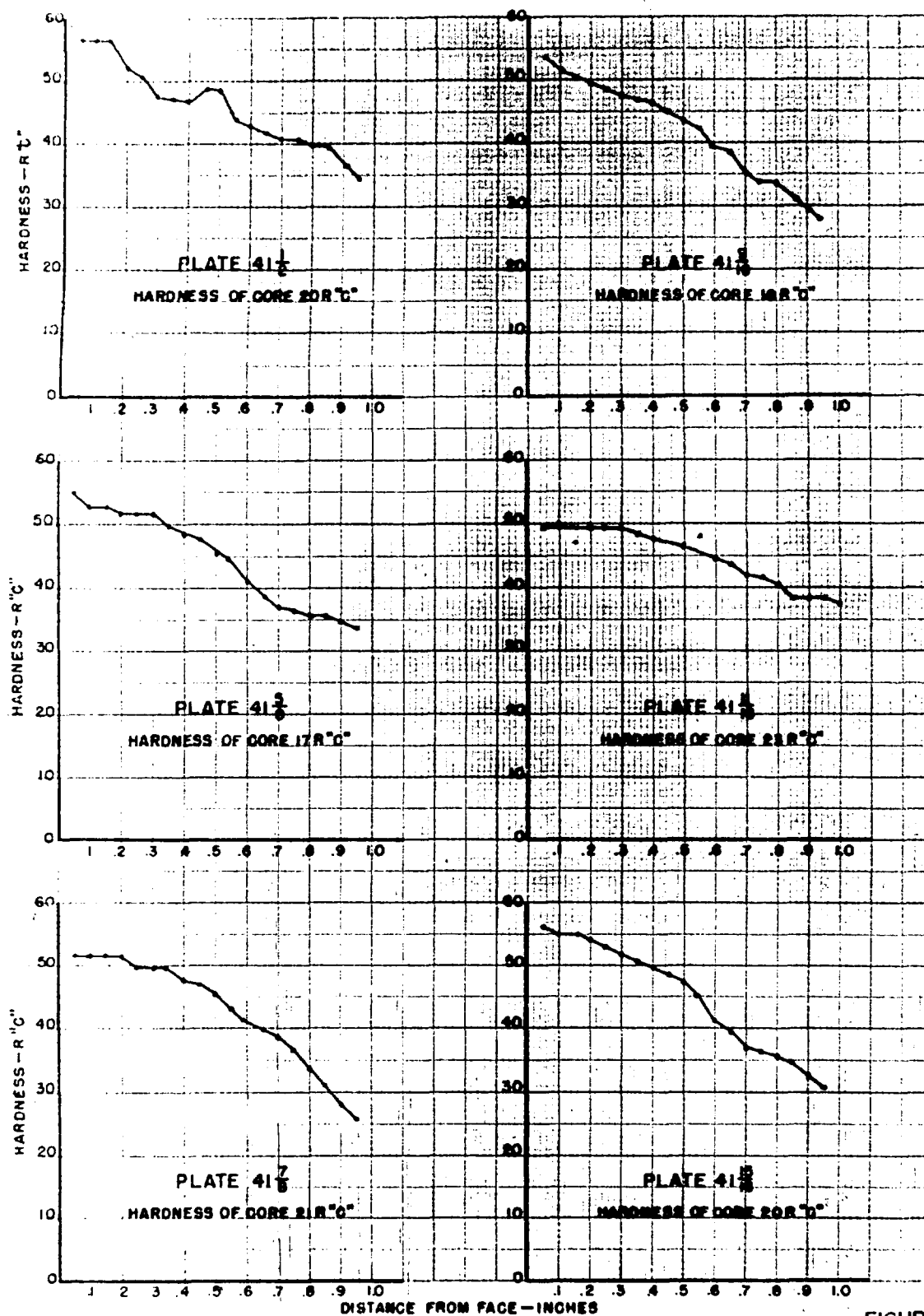
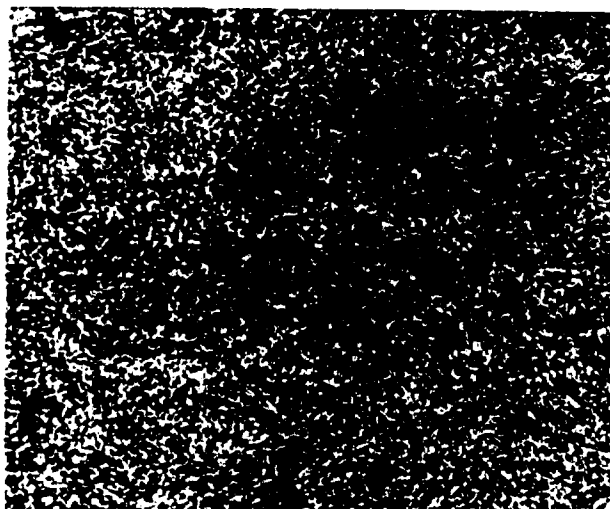


FIGURE 2

Microstructure of 2 $\frac{1}{2}$ " Thick Rolled Homogeneous
Armor Plates



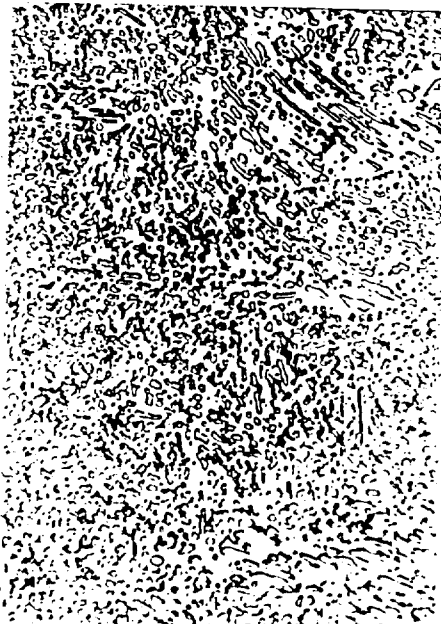
X1000 11A Picral
Tempered martensite.



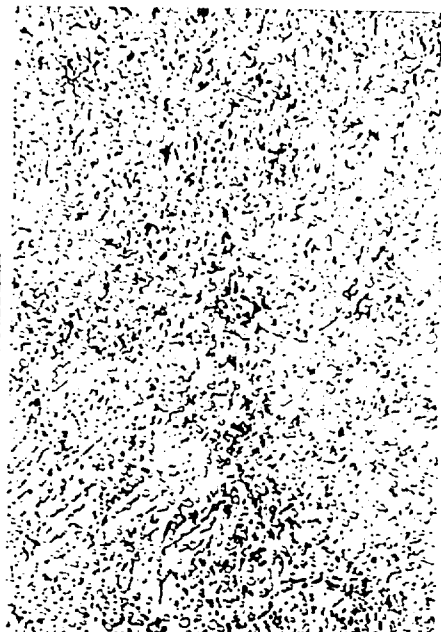
X1000 31A Picral
Tempered martensite.

Microstructure of 2 $\frac{1}{2}$ " Thick Rolled Face Hardened Armor Plates

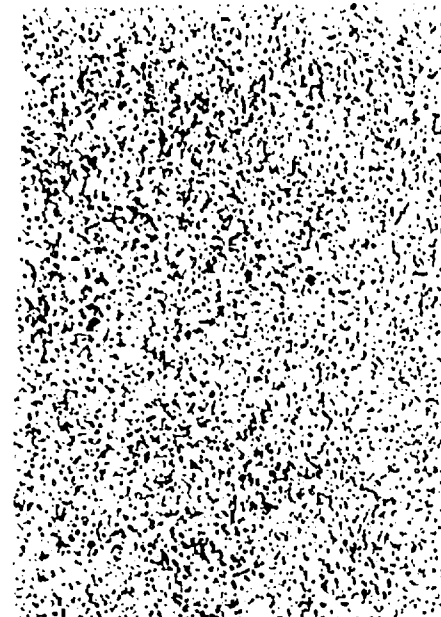
Plate 41 7/16



Outer case - Fine carbide plates in fine martensitic matrix .035" from case face.

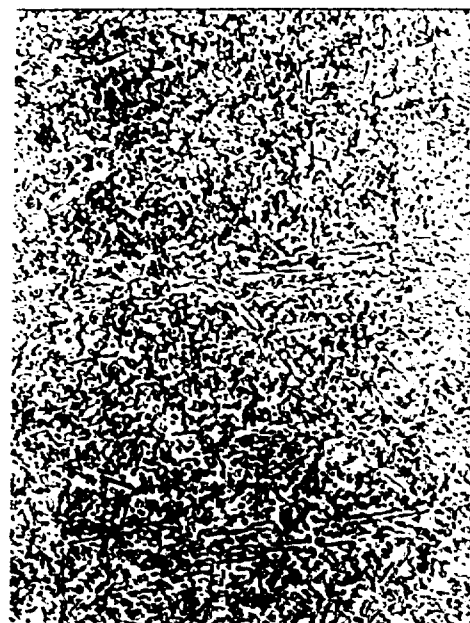


Inner case - Small globular carbides in fine martensitic matrix 0.25" from case face.



Uniform distribution of fine carbides in the core (dark areas similar to tempered bainite).

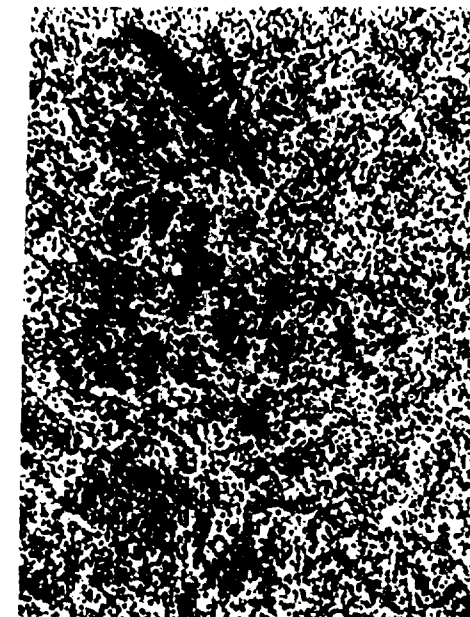
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Outer case - Fine carbide plates (Widmanstatten pattern) in a martensitic matrix .035" from case face.



Inner case - Globular carbides in fine martensitic matrix 0.25" from case face.



Uniform distribution of fine carbides in the core (dark areas similar to tempered bainite).

All photomicrographs X1000 - Pictoral Etch